Production of Charged Particles by Proton-induced Reaction at Intermediate Energy

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We measured the differential cross section of (p,p′x) and (p,dx) reactions by 300- and 392-MeV proton-induced reactions. The measurements were made for targets, ^{12}C, ^{27}Al, ^{93}Nb and ^{197}Au. We compared the mesurements with the Quantum Molecular Dynamics (QMD) model calculations. It is shown that QMD model calculations underestimate the differential cross section of (p,dx).

1.Introduntion

In recent years, nuclear data in the intermediate energy are required from various fields of basic physics and nuclear technologies. Differential cross sections and double-differential cross sections are needed for calculations of particle transport in matter. There are currently some available proton data of proton-induced reactions[1], but few systematic measurements above 200 MeV of incident energy. Data of complex particles, such as deuteron and alpha, are less than nucleon data. Especially, deuteron data is important to comprehend productions of heavier fragments, since a deuteron consists of a proton and a neutron with a small binding energy. It is interesting to study the mechanism of indirect pick up process that produces high energy deuterons. In order to develop a calculation code that is able to simulate the nuclear reactions as accurately as possible, comprehension of the process of deuteron production becomes important.

The purpose of this work is to measure differential cross sections and Double-differential cross sections of protons and deuterons in the incident proton energy at 300- and 392-MeV, and to compare the measurements with the Quantum Molecular Dynamics (QMD) model calculations.

2.Experimental and Data Analysis

The beam experiment was performed at the Research Center for Nuclear Physics (RCNP), Osaka University. A sketch of the experimental setup is shown in Figure 1. Protons accelerated up to 300 MeV and 392 MeV by the ring cyclotron were bombarded onto targets set at the center of a vacuum chamber. The measurements were made for targets, ^{12}C, ^{27}Al, ^{93}Nb and ^{197}Au. We measured energy spectra from 19.7° to 104.1° in laboratory frame.

The stacked GSO(Ce) scintillator spectrometer was used in the measurements. Stopping detectors, such as scintillator detectors are useful for measurements of proton spectra over a wide energy range[2-3].

Especially stacked spectrometers are suitable for these measurements in the intermediate energy region. The cerium doped gadolinium orthosilicate, $Gd_2SiO_5(Ce)$ - GSO(Ce), has several advantages such as a relatively high density and a high radiation hardness, and is suitable for experiments in this energy region. A stacked GSO(Ce) spectrometer was designed to measure continuum spectra from proton-induced reactions at incident energy of 200 - 400 MeV. A schematic diagram of the spectrometer is shown in Figure 2. It consisted of 10 mm, 2 mm (or 1 mm) and 5 mm thick plastic scintillators and two cubic and one cylindric GSO(Ce) scintillators. Coincidence among the signals from the plastic plates produced trigger signals for analog-to-digital converters. The 10 mm thick plastic scintillator had an aperture of 15 mm diameter and played as an active slit to determine the solid angle of the spectrometer. The size of GSO(Ce) scintillators used were $43 \times 43 \times 43$ mm^3 for cube and 62 mm in diameter and 120 mm long for cylinder.

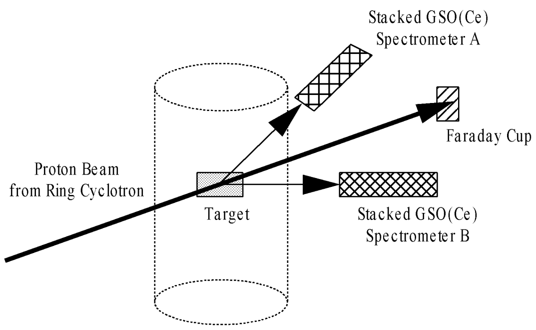

Figure 1: Layout of ES course

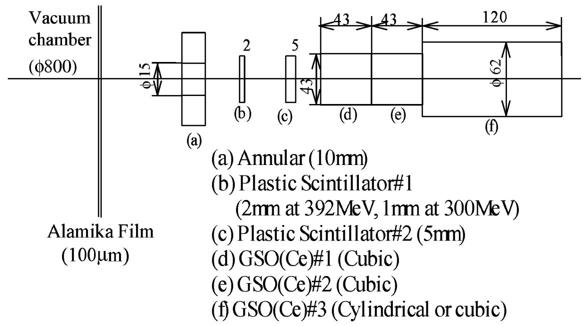

Figure 2: Stacked spectrometer with GSO(Ce) and plastic scintillators

The ΔE-E techniques were used in order to separate deuterons from protons[4]. Protons and deuterons concentrate on a well-defined locus like Figure 3. To obtain total number of several charged particles, first we divided them into several areas. Then the events corresponding to protons and deuterons were counted up respectively.

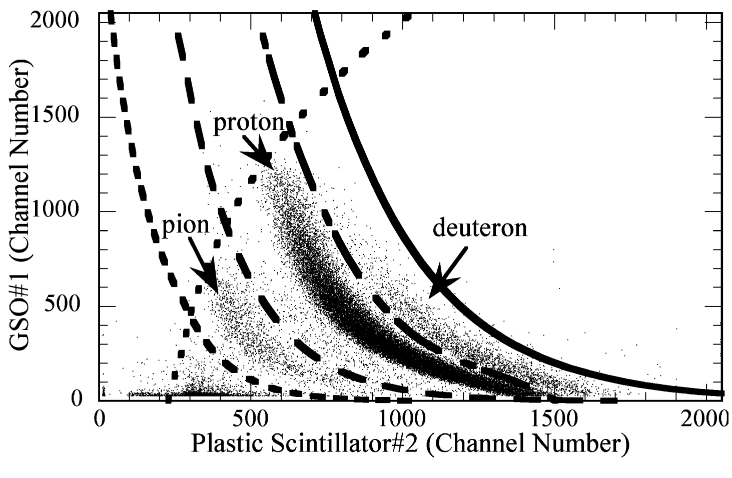

Figure 3: Particle-identification spectra of ΔE vs E

3.Results and Discussion

A. Target mass dependence

Differential cross sections obtained from the experiment via 300 MeV proton-induced reactions are shown in Figure 4 and Figure 5 for p and d, respectively. The abscissa shows the scattering angle. Every dot shows the results by measurement. First, we analyzed the the data of Gold. We assumed the angular distributions are well described by liner relations. Next, other nuclei were analysed by using the same relation but the strength is proportional to $A^{2/3}$ with respect to Gold data. The lines in Figure 4 and Figure 5 show the results of analysis.

In the same way, the results obtained via 392 MeV proton-induced reactions are shown in Figure 6 and Figure 7. Both differential cross sections of p and d are found to depend on $A^{2/3}$ approximately. Differential cross section for ^{27}Al, however, show different behavior from other targets.

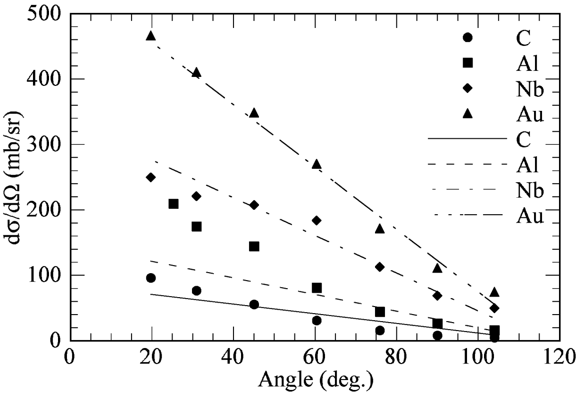

Figure 4: Angular distributions of proton production from 300 MeV proton-induced reactions

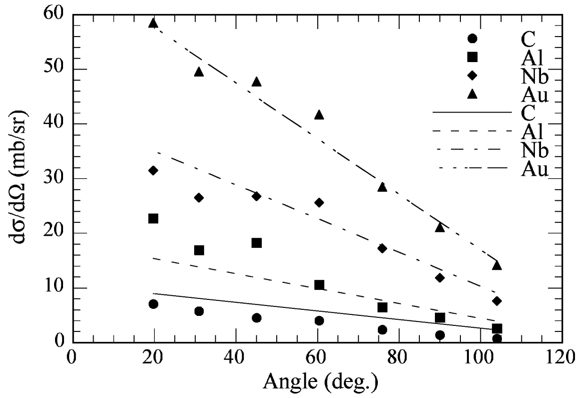

Figure 5: Angular distributions of deuteron production from 300 MeV proton-induced reactions

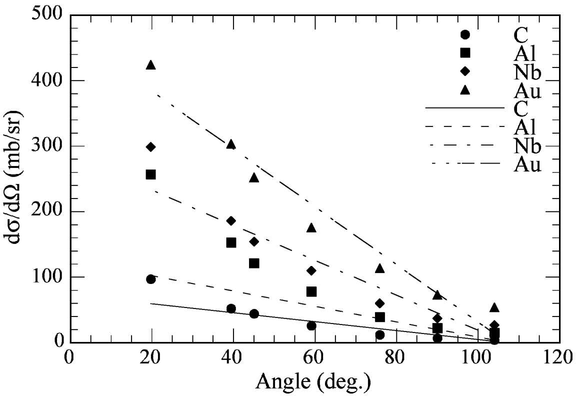

Figure 6: Angular distributions of proton production from 392 MeV proton-induced reactions

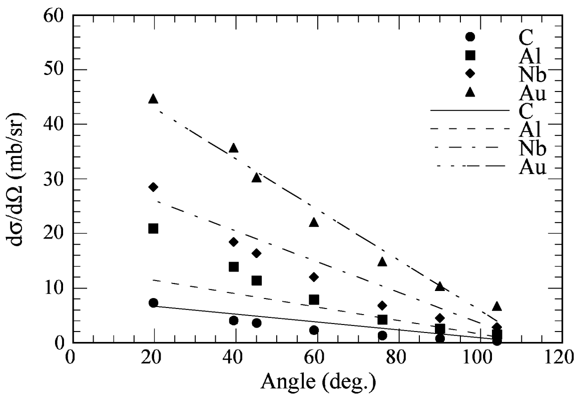

Figure 7: Angular distributions of deuteron production from 392 MeV proton-induced reactions

B.Comparison between mesurements and QMD model calculations

We compared the measurements with the QMD model calculation[5]. Differential cross sections obtained from the QMD model calculation via 300 MeV proton- induced reactions are shown in Figure 8 and Figure 9 for p and d,respectively. Every dot shows the results by measurement. The lines in Figure8 and Figure9 show the results of the QMD model calculation.

In the same way, the results obtained via 392 MeV proton-induced reactions are shown in Figure10 and Figure11. Differential cross sections of protons obtained from QMD model calculation agree with the measurements. (Figure 8, Figire 10) But, differential cross sections of deuterons obtained from QMD model calculation are much smaller than the measurements. (Figure 9, Figure 11)

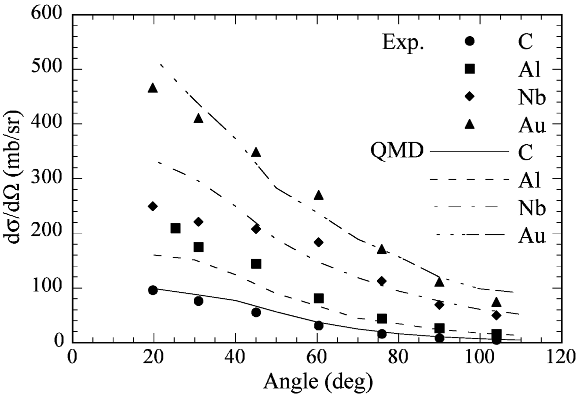

Figure 8: Comparison between the proton mesurements and QMD model calculations at incident proton energy of 300 MeV

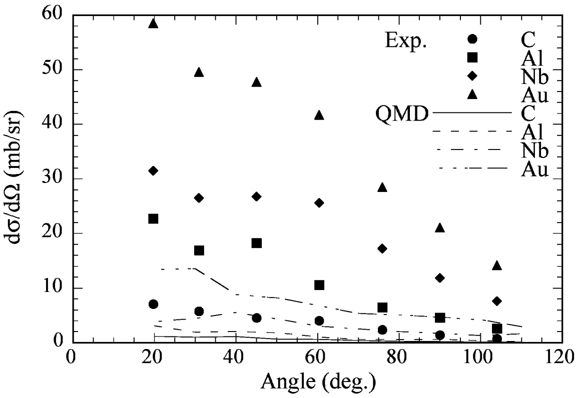

Figure 9: Comparison between the deuteron mesurements and QMD model calculations at incident proton energy of 300 MeV

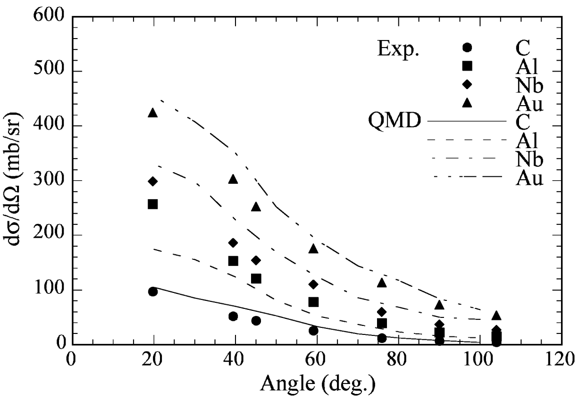

Figure 10: Comparison between the proton mesurements and QMD model calculations at incident proton energy of 392 MeV

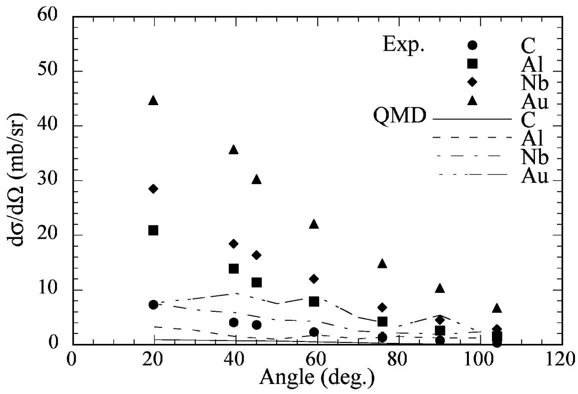

Figure 11: Comparison between the deuteron mesurements and QMD model calculations at incident proton energy of 392 MeV

4.Conclusion

Differential cross section of proton and deuteron productions were measured for proton-inducet reactions at 300- and 392-MeV. It is found that the production of p and d depend on $A^{2/3}$ approximately. A different behavior from other target nuclei are shown in ^{27}Al.

Differential cross sections of proton production reactions are consistent between QMD model calculations and the measurements. But, large discrepancies are seen in deuteron production reactions.

Reference

[1] R. E. Segel, et al. : Phys. Rev. C26, 2424 (1982).
[2] K. Anami, et al. : Nucl, Inst. Meth. A404, 327 (1998).
[3] H.Yosida, et al. : Nucl. Inst. Meth. A411, 46 (1998).
[4] A. A. Cowley, et al. : Phys. Rev. C45, 1745 (1992).
[5] Niita, K, et al. : Phys. Rev. C52, 2620 (1995).